Bulletin of Electrical Engineering and Informatics
Vol. 12, No. 2, April 2023, pp. 659~667
ISSN: 2302-9285, DOI: 10.11591/eei.v12i2.4553

Modeling of power numerical relay digitizer harmonic testing in wavelet transform

Emad Awada[1], Eyad Radwan[2], Mutasim Nour[3], Aws Al-Qaisi[4], Ayman Y. Al-Rawashdeh[5]
[1]Department of Electrical Engineering, Al-Balqa Applied University, Amman, Jordan
[2]Department of Electrical Engineering, Applied Science Private University, Amman, Jordan
[3]School of Engineering and Physical Sciences, Heriot-Watt University, Dubai Campus, United Arab Emirates
[4]Department of Communication Engineering, Al-Balqa Applied University, Amman, Jordan
[5]Department of Electrical Engineering, Al-Balqa Applied University, Amman, Jordan

Article Info

Article history:

Received Aug 12, 2022
Revised Sep 30, 2022
Accepted Oct 24, 2022

Keywords:

Digital power relay
Discrete wavelet transform
Harmonic distortion
Power system protection
Signal-to-noise ratio
Spurious-free dynamic range

ABSTRACT

In today's modern power devices and rapid growth power demands, the need for precise and accurate protection relays is a must for the power distribution system. That is, to segregate faulty sectors within fewer cycles, power relays should perform at the highest level of accuracy to detect abnormal conditions in power distribution. Therefore, this work will investigate the enhancement of the numerical relay testing in terms of harmonic distortions effect on the digitized output waveform as direct causes of relay failures. However, as it is an expensive process of testing the digitizing element of the numerical relay, this paper proposes a new algorithm of wavelet transforms in power quality signal processing testing using MATLAB simulation. As this newly proposed method of advanced waveform analysis algorithm will enhance the testing process of digitizing elements, and reduce data compiling complexity, a comparison between conventional fourier transforms testing and wavelet algorithm under abnormal conditions will be simulated based on inserting multi harmonics effect. As a result, based on the wavelet bank of filters, de-noising, and decomposition structure filters, wavelet has provided promising results in defining the effect of waveform distortion tripping time, fault location, total harmonic distortion, signal-to-noise ratio, and spurious-free dynamic range.

Corresponding Author:

Emad Awada
Department of Electrical Engineering, Al-Balqa Applied University Amman
Amman, Jordan
Email: emad.awada@bau.edu.jo

1. INTRODUCTION

In today's widespread population across the globe, and the fast revolution of technology from high voltage to low voltage power system networks, protection relay plays an important role in preserving the power system and eliminating abnormality within a few cycles [1], [2]. Yet, as power relay comes in different types and functions, such as current relay, and voltage relay, digital relays have developed more efficient functions in terms of current, voltage, and frequency measurement accuracy and power automation systems [3], [4]. Therefore, this work will investigate the numerical relay in terms of the internal logical microprocessor digitizing process as the bottleneck between the real and digitized spectrum to enhance the operation of power system protection. As known, the power system is subject to many interferences as an open surrounding power generation, transmission line, and distribution which result in a high rate of distortion fault occurrence [2], [5], [6]. In addition, with the significant growth of non-linear electronic types of equipment load, such as AC and DC variable speed drivers, switch mode power supplies, and power semiconductor controllers, harmonics are generated in voltage and current waveforms due to nonsinusoidal current draw and feed back into the power system. As a result, harmonic affects both electromechanical and digital relays by producing a pure signal beyond the fundamental frequency [7]–[11]. As a result, the North American electric reliability corporation (NERC) has mandated four reliability standards for the US government electronic return originator (REO) jurisdiction to insure power system protection and control. Standards such as; PRC-008 under frequency and Shedding, PRC-011 undervoltage load shedding, PRC-017 special protection, and testing program, and PRC-005 transmission and generation protection deal directly with relay operation and testing [12] as a major element in power system monitoring, measuring, and controlling protection process. Traditionally, static electro-mechanical relays were widely used to provide sole function characteristics [2], [3]. However, with the fast growth of power system generation and distributions, and dynamic changes in transmission and distribution grid, the technology of power relay technologies have evolved in the past few decades to provide multi-function characteristics. That is, by monitoring multiple input parameters, electronic relays based on digitized discrete electronic microprocessors were developed. Yet, as numerical relays algorithm structures are based on digitizing, and signal processing of analog current and voltage input waveform, relay digitizing operation constitutes a major data acquisition in terms of electrical quantities, accuracy, and speed [13], [14].

Many researchs have been conducted in the area of testing digital relay output waveforms to ensure the integrity of proper system performance. According to Wannous and Toman [3], a study was performed by investigating harmonics impact through the fast fourier transform (FFT) algorithm by injecting high values harmonics. Others had studied the practical effect of harmonic influences on electromechanical and microprocessor relays fundamental tone [7]–[10]. Some studies had explored the cost associated with quantifying the reliability and power quality as in [15]–[17] in terms of harmonics influences. However, the testing methodology of analog digitizers had shown a costly process in addition to some disadvantages as will in terms of a large number of samples, compiling duration, and calibration process [2], [3], [14], [18]. For instance, in testing digitizer characteristics, stimulus sine waveforms were primarily used as a simple mathematical model, and the easiest waveforms to generate frequencies with satisfactory reliability [19], [20]. Meanwhile, other types of waveform, square waves, for example, have been solely used for testing. As a result, in this work, the focus will be to investigate digital relay digitizer operation in terms of the real-time function waveform by implementing a new effective testing algorithm of wavelet transform into the microcontroller relay to ensure accurate measurement of power waveform dynamic operation and quantization process.

2. THEORETICALCAL BACKGROUND

In digitizing analog current or voltage waveform, several blocks of the filter process are used, to remove high-frequency components from the digitized waveform [3], [14], [19]. With a sampling frequency of 4,000 samples per second for 50 Hz frequency, IEC standard 61850, a large number of quantized data is inserted into the digital sinusoidal signal. Filters are adjusted to match amplitude angle using Fourier transformation as shown in Figure 1. Ideally, as the relay digitizer converts analog current and voltage waveform into the digital waveform, no additive or missing data due to quantization and sampling prosses are accounted for.

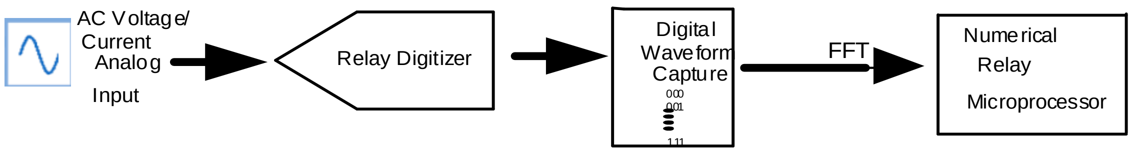

Figure 1. Digitizing process of the analog power waveform

Yet, in a real-time application, generated digital signal would have an error embedded in the original waveform which affects system performance. As analog waveform X(t) converted to the digital domain, the output waveform X(n) can be presented with an error added as in (1).

$$\mathrm{X}\,(\mathrm{n}) = \mathrm{X}(\mathrm{t}) + \mathrm{e} \tag{1}$$

Where Xin(t) is the original signal and e is error value.

Therefore, testing parameters of the relay digitizer should be a crucial factor to define the accuracy of the converted signal. Parameters such as multi-harmonics effect, signal to noise ratio (SNR), total harmonic distortion (THD), and spurious-free dynamic range (SFDR) have a major effect on fundamental waveform [3], [18]–[20]. Noise and non-linear load distortion result in major harmonics alteration to fundamental waveform due to an increase in rms component value [3], [18], [21]. The power of these undesired digitized waveform components would affect the purity of the digitized waveform as in IEEE Std. 1241802.11g for SNR. That is, the ratio of signal power to the undesired signal components power, as noise and quantization error, as in (2).

$$SNR(dB) = 20\, log\, \frac{Psignal_{rms}}{Pnoise_{rms}} \quad (2)$$

Meanwhile, as sensitive loads are affected by harmonic distortion, IEEE Std. 1241 defines THD as the power ratio of harmonics power summation to the fundamental waveform power as in (3).

$$THD = \frac{P_2+P_3+P_4+\ldots+P_\infty}{P_1} \quad (3)$$

For the current waveform, THD is the ratio of RMS summation to the fundamental waveform as in (4).

$$THD(i) = \frac{\sqrt{\sum_{j=2}^{\infty} I_{jrms}^2}}{I_{rms}} * 100\% \quad (4)$$

Meanwhile, for voltage waveform components, THD can be shown as in (5).

$$THD(v) = \frac{\sqrt{\sum_{j=2}^{\infty} v_{jrms}^2}}{v_{rms}} * 100\% \quad (5)$$

Where vj is RMS voltage.

Such a phenomenon will degrade the original converted signal and lead to SFDR. That is, in IEEE Standard 1241, SFDR is the ratio of discrete fourier transform (DFT) regenerated digital signal amplitude to the largest harmonic (spurious) component observed over the full Nyquist band [19], [22], [23].

$$SFDR = 20\, log(\frac{Amplitude\ \ of\ \ Fundamental\ \ (RMS)}{Amplitude\ \ of\ \ Largest\ \ Spur(RMS)}) \quad (6)$$

3. NUMERICAL RELAY OPERATION AND TESTING

In the state-of-the-art power systems protection scheme, numerical relays are used with the advantage of programmable characteristics. Unlike conventional electromechanical and static relays, numerical relays do not require manual wiring and setting adjustments. Typically, numerical relay operation is based on measuring electric parameters in a network and converting measurements into digital mathematical and logical data to detect electrical faults and protect the network system. That is, a preset value of current or voltage needs to be defined as a threshold for numerical relay microprocessors to operate and disconnect from the electrical network [2]. Therefore, with quantizing binary inputs, configurable outputs, and programmable logic as shown in Figure 1, the digitizing process is an essential. Using a step-down voltage or current transformer, the secondary low side passes into a low-pass filter before digitizing which must have a high level of accuracy and sampling frequency at least twice the cycle of the highest frequency. Therefore, the proper digitization process of the numerical relay is very critical to ensur fundamental tone rather than distorting the waveform.

As the conventional testing practice of analog digitizers based on waveform transformation, Fourier Transform is the core algorithm used in the frequency domain. Yet, as the fourier transform is based on the summation series of sine and cosine waveforms, characteristics of spectral impurity such as noise, harmonics, and frequency drifts may add and affect the digitizer testing output integrity [19]. As fourier transform articulates signals in the frequency domain, there will be no time representations in such an algorithm [19], [23]–[26].

4. METHOD

In this work of testing the performance of numerical power relay digitizer, a model of relay harmonics effect was simulated based on distorted digital waveform. MATLAB simulation was used to generate a single phase power waveform, as shown in Figure 2, with the presence of noise distortion and hamanic effects. As power relay connected to power distribution system, four stages of convervation will be perform; i) voltage/current step-down transformation, ii) relay digitizer converter circuit (analog to digital), iii) digital waveform data capture, and (iv) voltage/current data transformation for compiling process as shown in Figure 3. In this work, the simulated digitize output data was captured, analyzed, and validated through a model of conventional algorithm (fourier transform) and the new propesd algorithm (wavelet transform). Based on wavelet filter banks of denoising, decomposition, and localization in time and frequency domain, the behavior of power relay digitizer was monitored through extracting the detail components of output waveform and compiling SNR, THD, and SFDR as a major effect on numerical relay accuracy performance.

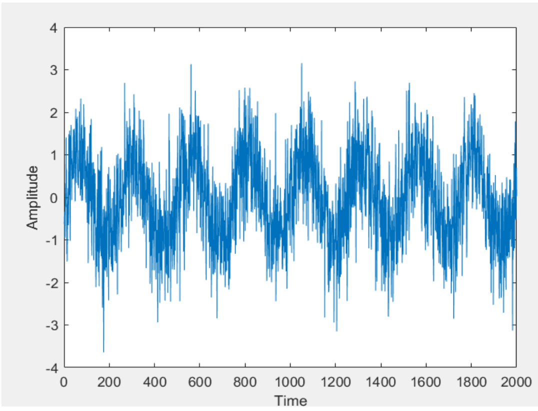

Figure 2. Simulated relay digital output waveform

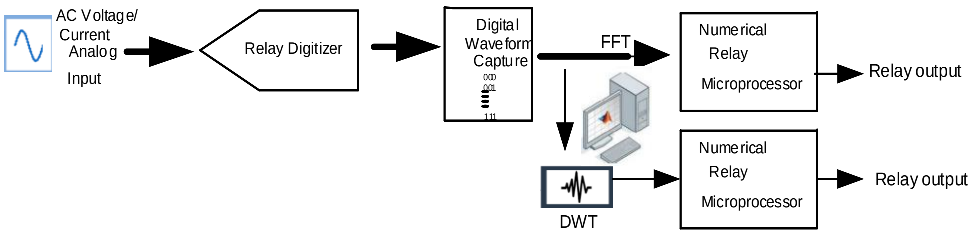

Figure 3. A newly proposed testing technique

5. RESULT AND DISCUSSION

As both algoritms of fourier and wavelet transformation were applied to analyze power relay output data, specific characteristics performance were tested, as follow, under abnormal and various fault types conditions. Several types of mother wavelet were applied to compare power relay digitizer fault mesearments with conventional algorithms in terms of SNR, THD, and SFDR.

5.1. Signal to noise ratio

In this simulation model, relay digital output waveforms were analyzed through FFT rather than DFT as a faster version. In addition, wavelet transform algorithm was used in computing SNR. By comparing the level of the signal components to the level of noise components in the signal background, the SNR of the digitized relay waveform was determined in terms of the ratio of signal power to noise power based on compiling all collected data samples in FFT as shown in Figure 4 and Table 1.

Meanwhile, using the unique property of the wavelet decomposition process, providing significant information about frequency components, DWT was used to determine SNR based on much fewer samples. By decomposing the relay digitized waveform into multi-level and keeping the energy of the signal. In this work, 2nd level decomposition was used to determine SNR based on detail coefficients cD2 as shown in Figures 5, 6, and Table 1. By comparing the computed SNR, it was clear that the Daubechie10 (Db10) had outperformed all other types of wavelet with SNR deviation of 1.35% from the FFT.

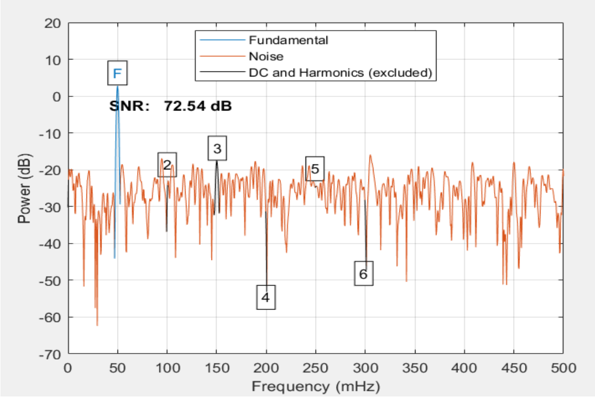

Figure 4. SNR of digitized relay waveform by FFT

Table 1. SNR of digitized relay waveform by FFT and DWT

Frequency	FT	Db12	Db10	Coef1	Haar	Bior3-1
50 Hz	72.54	68.17	70.43	81.21	53.21	82.04
60 Hz	71.48	67.89	69.75	94.31	51.82	86.95

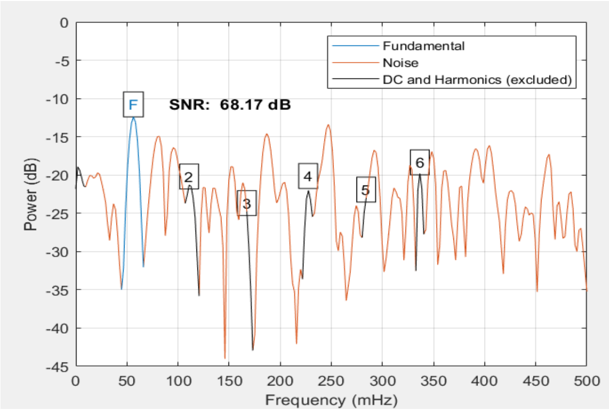

Figure 5. SNR of digitized relay waveform by DWT

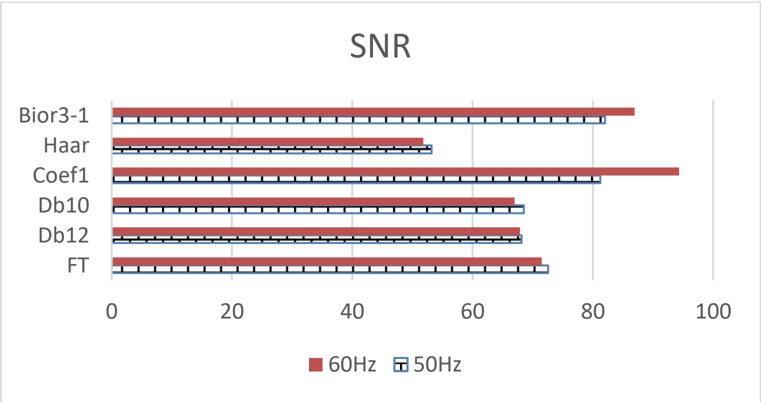

Figure 6. SNR reading illustration based on Table 1

5.2. Total harmonic distortion

As non-linear load feedback harmonics distortion into the power system's, the perfect power waveform accumulat changes into the fundamental powert tone. Such accumulation leads to distorting power sinusoidal waveform based on harmonic components magnitudes. In this work, both FFT as shown in Figure 7 and wavelet algorithms were applied to compute the effect of harmonics accumulation in terms of THD. 2nd level decomposition detail coefficients was used to determine the full scall range (FSR) of the relay output. By obtaining the summation square root of the differences between the detail coefficients and FSR, THD was measured based on the ratio of the square root to the maximum detail value (fundamental) as shown in Figures 8 and 9, Table 2. As a result, with 1.32% THD deviation from the FFT, Db10 had shown promissing results as comparing to other types of wavelet.

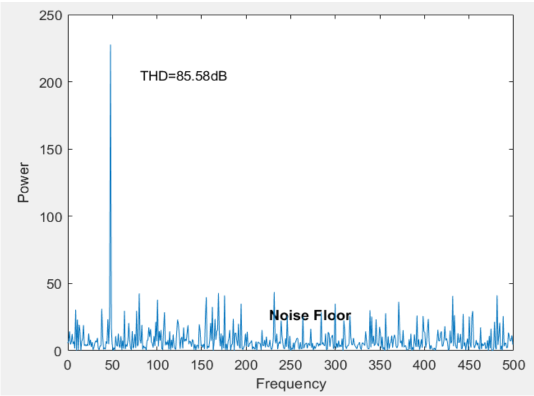

Figure 7. THD of digitized relay waveform by FFT

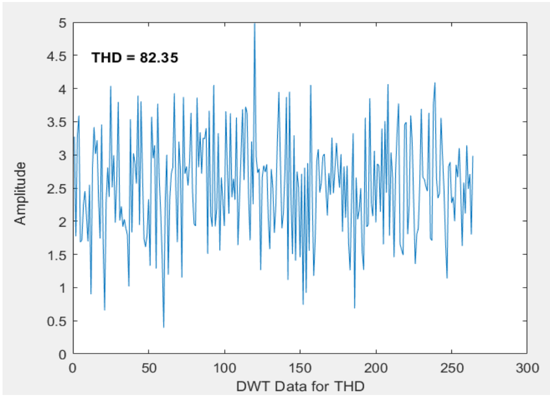

Figure 8. THD of digitized relay waveform by DWT

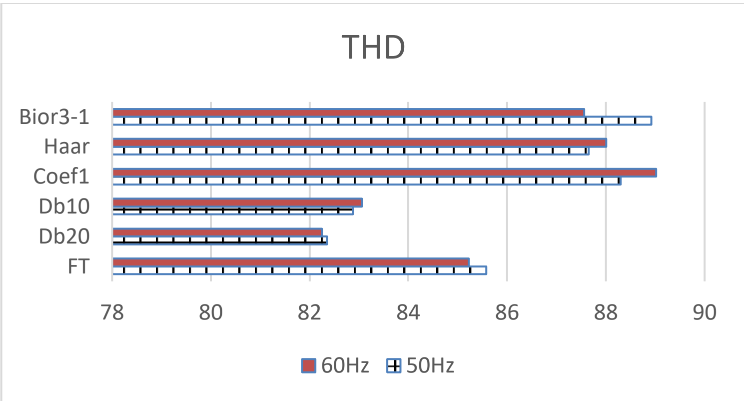

Figure 9. THD reading illustration based on Table 2

Table 2. THD of digitized relay waveform by FFT and DWT

Frequency	FT	Db20	Db10	Coef1	Haar	Bior3-1
50 Hz	85.58	82.35	83.06	88.30	87.65	88.92
60 Hz	85.22	82.25	83.28	89.02	88.01	87.56

5.3. Spurious-free dynamic range

By defining the ratio of fundamental signal RMS to the worst spurious of interfered signals (noise and harmonics), SFDR distinguishes fundamental and largest component of unwanted interfering error. As a result, it is critical to determine SFDR in digital power relays to ensure proper operation response to grid frequency. In this simulation work, SFDR was measured based on 50 Hz and 60 Hz using both algorithms of FFT power spectrum and wavelet instantaneous dynamic range as shown in Figures 10 and 11 respectively. SFDR output results for FFT and wavelet analysis (2nd level detail coefficients), were illustrated in Table 3 and Figure 12. From Table 3 and Figure 12, once a gain the Db10 had outperformed all othe types of wavelet with SFDR deviation of 1.39% from the FFT.

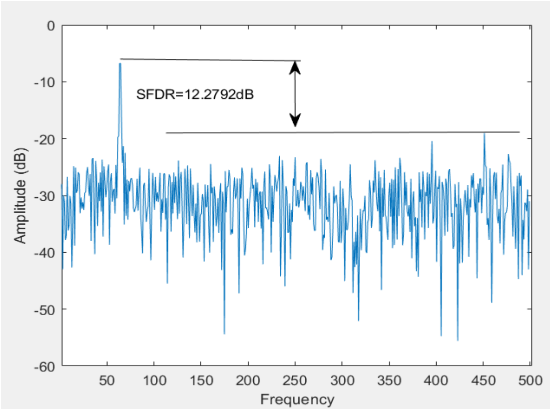

Figure 10. SFDR of digitized relay waveform by FFT

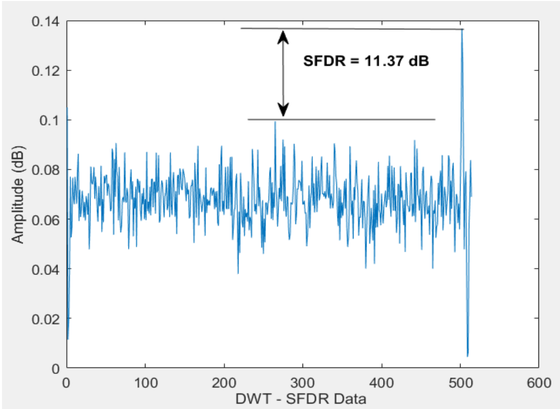

Figure 11. SFDR of digitized relay waveform by DWT

Table 3. SFDR of digitized relay waveform by FFT and DWT

Frequency	FT	Db12	Db10	Coef1	Haar	Bior3-1
50Hz	12.27	11.37	11.96	15.44	14.46	15.98
60Hz	13.23	11.92	12.85	16.23	16.08	15.96

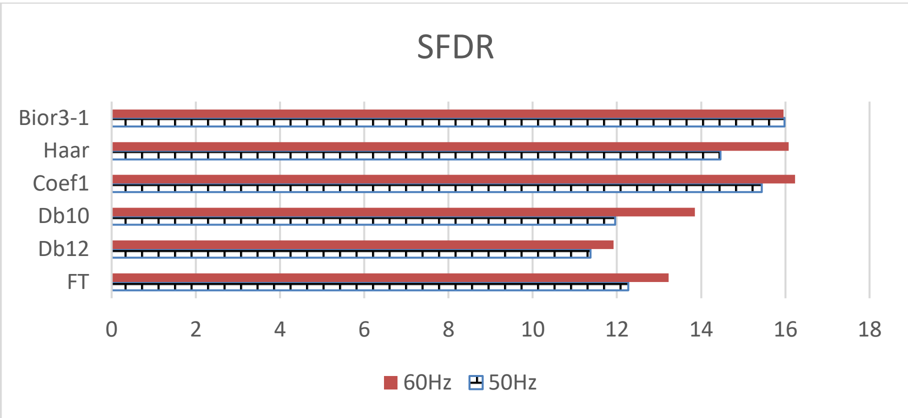

Figure 12. SFDR reading illustration based on Table 3

6. CONCLUSION

As shown in this work, the digital power relay output waveform was tested to ensure proper performance of the digitizer and microprocessor for relays to protect transformers and power lines reliably when harmonics are involved. Both algorithms of FFT and discreet wavelet transform were used to compare testing results, performance time, data filtering, and compiling processes. Based on two fundamental frequencies, 50 Hz and 60, the sampling rate of 4,000 Hz, a total of 2,000 sample data points was collected and compiled based on FFT. Meanwhile, for the discreet wavelet decomposition, the 2^{nd} level of detail side had dropped the total number of data samples to 514 points. As a result, parameters of the relay output waveform such as SNR, THD, and SFDR were tested with fewer data samples to compile resulting in less complexity and shorter testing time, as will. In addition, based on these testing results, it was clear that daubechies wavelet (Db10), with average mesurment deviation of 1.35% from the FFT, was one of the most appropriate mother wavelet to conduct power waveform analysis based on the specific sinusoidal shape that match current and voltage sinusoidal waveform.

REFERENCES

[1] C. McTaggart, J. Cardenas, A. Lopez, and A. Bone, "Improvements in power system integrity protection schemes," in *10th IET International Conference on Developments in Power System Protection (DPSP 2010). Managing the Change*, 2010, pp. 162–162, doi: 10.1049/cp.2010.0274.

[2] E. Awada, "Numerical voltage relay enhancement by integrated discrete Wavelet transform," *Journal of Southwest Jiaotong University*, vol. 56, no. 6, pp. 843–854, Dec. 2021, doi: 10.35741/issn.0258-2724.56.6.74.

[3] K. Wannous and P. Toman, "Evaluation of harmonics impact on digital relays," *Energies*, vol. 11, no. 4, pp. 1–20, Apr. 2018, doi: 10.3390/en11040893.

[4] U. Ehsan *et al.*, "A detailed testing procedure of numerical differential protection relay for EHV auto transformer," *Energies*, vol. 14, no. 24, pp. 1–21, Dec. 2021, doi: 10.3390/en14248447.

[5] M. Wei, W. Liu, H. Zhang, F. Shi, and W. Chen, "Distortion-based detection of high impedance fault in distribution systems," *IEEE Transactions on Power Delivery*, vol. 36, no. 3, pp. 1603–1618, Jun. 2021, doi: 10.1109/TPWRD.2020.3011930.

[6] A. M. Ahmad, N. Ijaz, M. E. Hassan, and M. Mehdy, "Reduction of harmonic distortion in power system during fault occurrence," *Journal of Energy Technologies and Policy*, vol. 8, no. 5, pp. 1–7, 2018.

[7] L. A. -Musawi, A. Waye, N. A. -Mutawaly, and W. Yu, "The effects of waveform distortion on power protection relays," *International Protection Testing Symposium*, pp. 1–7, 2013.

[8] F. Wang and M. H. Bollen, "Classification of component switching transients in the viewpoint of protective relays," *Electric Power Systems Research*, vol. 64, no. 3, pp. 197–207, Mar. 2003, doi: 10.1016/S0378-7796(02)00170-0.

[9] Y. G. Paithankar, "Line protection with distance relays," in *Transmission Network Protection: Theory and Practice*, New York, USA: CRC Press, 1998, pp. 296–321.

[10] S. E. Zocholl and G. Benmouyal, "How microprocessor relays respond to harmonics, saturation, and other wave distortions," in *Proceedings of the 24th Annual Western Protective Relay Conference*, 1998, pp. 1–15.

[11] G. Achleitner, L. Fickert, C. Obkircher, and M. Sakulin, "Earth fault distance protection," *20th International Conference on Electricity Distribution*, pp. 1–4, 2009, doi: 10.1049/cp.2009.0670.

[12] NERC, *Supplementary reference and FAQ*, no. October. Atlanta, Georgia: North America Electric Reliability Corporation, 2015.

[13] E. A. Awada, "Hilbert based testing of ADC differential non-linearity using Wavelet transform algorithms," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 8, no. 6, pp. 5071–5079, Dec. 2018, doi: 10.11591/ijece.v8i6.pp5071-5079.

[14] E. A. Awada, "The algorithm of testing ADC effective, number of bits based on hilbert and Wavelet transform," in *Proceedings of the 2019 3rd International Conference on Information System and Data Mining-ICISDM 2019*, 2019, pp. 196–200, doi: 10.1145/3325917.3325921.

[15] R. Leao, G. C. Barroso, N. X. Melo, and R. F. Sampaio, "Numerical relay: influenced by and accessing the power quality," in *Power Quality*, no. April, A. Eberhard, Ed. Rijeka, Croatia: InTech, 2011, pp. 213–236, doi: 10.5772/13891.

[16] S. Elphick, P. Ciufo, V. Smith, and S. Perera, "Summary of the economic impacts of power quality on consumers," in *2015 Australasian Universities Power Engineering Conference (AUPEC)*, Sep. 2015, pp. 1–6, doi: 10.1109/AUPEC.2015.7324875.

[17] I. Daut, S. Hasan, and S. Taib, "Magnetizing current, harmonic content and power factor as the indicators of transformer core saturation," *Journal of Clean Energy Technologies*, vol. 1, pp. 304–307, 2013, doi: 10.7763/JOCET.2013.V1.69.

[18] E. A. Awada, M. H. Alomari, and E. Radwan, "Wavelet estimation of THD based on Hilbert transform extraction," *International Journal of Applied Engineering Research*, vol. 11, no. 9, pp. 6451–6456, 2016.

[19] A. Busacca *et al.*, "Switching frequency effects on the efficiency and harmonic distortion in a three-phase five-level CHBMI prototype with multicarrier PWM schemes: experimental analysis," *Energies*, vol. 15, no. 2, pp. 1–29, Jan. 2022, doi: 10.3390/en15020586.

[20] S. Vlahinic, D. Brnobic, and N. Stojkovic, "Indices for harmonic distortion monitoring of power distribution systems," in *2008 IEEE Instrumentation and Measurement Technology Conference*, May 2008, pp. 421–425, doi: 10.1109/IMTC.2008.4547072.

[21] N. S. Dudhe and D. B. Aghmare, "Application of Wavelet transform in power system analysis and protection," *International Journal of Engineering Research and*, vol. V6, no. 05, pp. 889–892, 2017, doi: 10.17577/ijertv6is050511.

[22] W. Kester, "Understand SINAD, ENOB, SNR, THD, THD^+ N, and SFDR so you don't get lost in the noise floor," *Analog Devices*, pp. 1–8, 2009.

[23] A. Skamyin, A. Belsky, V. Dobush, and I. Gurevich, "Computation of nonlinear load harmonic currents in the presence of external distortions," *Computation*, vol. 10, no. 41, pp. 1–15, Mar. 2022, doi: 10.3390/computation10030041.

[24] P. K. Ray, B. K. Panigrahi, P. K. Rout, A. Mohanty, and H. Dubey, "Detection of faults in a power system using Wavelet transform and independent component analysis," in *Proceedings of the International Conference on Advancement of Computer Communication and Electrical Technology, ACCET 2016*, 2017, no. October, pp. 1–5, doi: 10.1201/9781315400624-45.

[25] E. A. Awada, "Analysis of SFDR using power spectrum based on Wavelet extraction," *International Journal of Applied Engineering Research*, vol. 11, no. 2, pp. 1256–1260, 2016.

[26] A. Hovanessian and M.-A. Norouzi, "Islanding detection using Wavelet transform and rate of change of frequency relay method in presence of different distributed generation technologies," *IEEJ Transactions on Electrical and Electronic Engineering*, vol. 11, pp. 68–77, Jun. 2016, doi: 10.1002/tee.22238.

BIOGRAPHIES OF AUTHORS

Emad Awada B.S. in Electrical Engineering from Prairie View Texas A&M University (PVAMU) in 1998. M.S. and Ph.D. in Electrical Engineering, PVAMU 2006 and 2011 respectively. His work experiences are in power energy, protection, sustainability, renewable energy, and signal processing. He is a full-time at Department of Electrical Engineering, Al-Balqa Applied University. He can be contacted at email: emad.awada@bau.edu.jo.

Eyad Radwan BSc. from JUST in 1996, MSc. and PhD. fromUPM (Malaysia) in 1999 and 2004 respectively. His specialization is in the area of electrical power, drives, and control. He can be contacted at email: e_redwan@asu.edu.jo.

Mutasim Nour Associate Professor at the Heriot-Watt University Dubai Campus. A member of IEEE and Director of studies for MSc energy and renewable energy engineering programmers. He can be contacted at email: mutasim.nour@hw.ac.uk.

Aws Al-Qaisi Associate Professor at Al-Balqa Applied University, and member of the IEEE executive committee in Jordan. His research interests are digital signal processing, feature extraction, and wireless communication. He can be contacted at email: aws.alqaisi@bau.edu.jo.

Ayman Y. Al-Rawashdeh Associate Professor at Al-Balqa Applied University. His main research interests include renewable energy, drive system analysis, and simulations. He can be contacted at email: r.ayman.rawashdeh@bau.edu.jo.